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Ninth Cambridge Workshop on

Cool Stars, Stellar Systems, and the Sun

Annual Report

The Ninth Cool Stars Workshop was held in Florence, Italy from October 3 to 6, 1995. There were almost 300 participants presenting talks on four main topics:

- X-ray and EUV Coronal Spectroscopy
- Mass Loss and Winds from Cool Stars
- Cool Stars in Clusters and Associations
- Recent Advances in Solar Physics

Discussion Sessions were held on;

- Near IR Spectroscopy
- Very Low Mass Stars
- Star Formation and Early Stellar Evolution
- Active Binaries

The Proceedings of the Workshop will be edited by R. Pallavacini and A. K. Dupree and published by the Conference Series of the Astronomical Society of the Pacific. Attached is the contribution to the Proceedings by A.K. Dupree.

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and

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N.S. Brickhouse, A.K. Dupree, and J.C. Raymond
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EUVE Spectroscopy of Active Binaries

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Abstract. EUVE spectra have been analysed from a sample of binaries of RS CVn and W UMa-type (44ι Boo, HR 1099, UX Ari, Capella, VY Ari, and λ And). Coronal material occurs at all coronal temperatures (10^6–$10^{7.3}$ K). A narrow high temperature enhancement (a "bump") is present in the emission measure distributions for short-period (P$\leq$ 13 d) binary systems similar to that originally found in *Capella.* Previous analysis of rapidly rotating single stars revealed similar emission measure enhancements. Coronas of rapidly rotating stars contain a new structure that is absent in coronas of slowly-rotating stars like the Sun. This structure may be the coronal manifestation of the high-latitude or polar spots identified in the photosphere through Doppler imaging and photometric studies.

1. Introduction

The EUVE satellite is obtaining extreme ultraviolet spectra of cool stars in the wavelength region 70 to 700 Å. From the very first results (Dupree *et al.* 1993, Brown 1994, Monsignori-Fossi & Landini 1994, Drake *et al.* 1995, Mewe *et al.* 1995), it was apparent that the EUVE spectrometers can obtain superb spectra of cool stars. Rich emission lines, predominantly from iron, dominate the spectra and yield unique and explicit information on the temperature structure of their coronas. The in-orbit performance of the spectrometers is described by Boyd *et al.* (1994). The spectra discussed here were obtained through NASA's Guest Observer Program or transferred from the Public Archives. All spectra were reduced at the Center for Astrophysics as described in Dupree *et al.* (1993).

2. Spectral Analysis

The goal is to investigate the structure of the stellar corona producing the EUV spectrum and identify the stellar parameters that are the systematic determinants of that structure. The quantity of interest is the emission measure of the atmosphere:

$$EM = N_e \; N_H \; \Delta V_{(\Delta T)} \tag{1}$$

which must be defined over a temperature interval, here taken to be 0.1 dex. This quantity represents the amount of material required at each temperature to produce the observed spectrum.

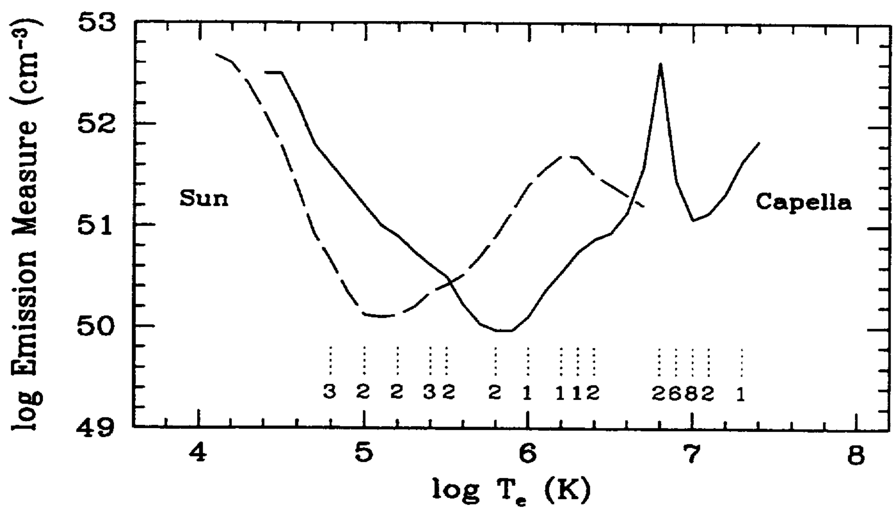

Fig. 1: The emission measure distribution for the Sun [a cell center model (scaled) from Raymond and Doyle 1981] and *Capella* (Dupree *et al.* 1993). The broken vertical lines indicate the approximate position in temperature of formation and the number of the strong ultraviolet and extreme ultraviolet lines used to define the emission measure. These lines have been measured in *Capella* with *IUE* and *HST* (between $\lambda\lambda$1200–1600), *ORFEUS* (between $\lambda\lambda$912–1176) and *EUVE* (between $\lambda\lambda$90–370).

We proceed as follows: we first select strong identified lines, extract their fluxes, and correct for interstellar hydrogen and helium absorption to obtain the (unabsorbed) line flux observed at the Earth. Next, evaluation of atomic level populations is made with multi-level atoms including allowed and metastable levels and the many transitions among them caused by electron and proton collisions. For calculations of the level populations, an electron density is generally assumed, based on electron density diagnostics or detailed spectral synthesis of selected spectral regions. A grid of electron densities is usually evaluated. These calculations are made with current atomic physics and rate coefficients (Brickhouse *et al.* 1995). The emission rates are integrated through a test atmosphere, and the atmosphere (or, equivalently, the emission measure distribution) is modified until the predicted fluxes from the models match the observed fluxes. Strong lines are generally reproduced by the emission measure to better than a factor of two. Typically, for spectra with good signal-to-noise ratios, the deviation between the prediction of the continuous emission measure distribution model and the observed flux is better than 30%. Such an error translates directly into a comparable error in the emission measure itself. This emission measure defined by the strong lines can then be used to predict the weaker species to facilitate further line identifications and refine the model. In fact, the summed *Capella* spectra are of such high quality that the bremsstrahlung continuum can be measured directly at short wavelengths between the emission lines to provide additional checks on the high temperature structure (Brickhouse 1996).

Our iterative method (Dupree *et al.* 1993; Brickhouse 1996) has advantages over global spectral fitting procedures (Mewe *et al.* 1995) because it depends only on well-measured data with reliable fluxes, and because the emission measure curve is not constrained to a simple "smooth" approximation, but allowed to reflect the physics inherent in the observed line emission spectrum. Moreover the fit is not degraded by bins containing noise or weak signals as occurs in global procedures (*cf. also* Schmitt *et al.* 1996).

This iterative method must replace earlier "approximations" to the contribution function of a specific ion that depend upon a smooth variation of the temperature profile. These approximations were developed originally for the Sun, but the smooth temperature variation is not found in active stars, as demonstrated by the *Capella* analysis.

3. The Emission Measure of Capella

Results for the binary system *Capella* illustrate (Fig. 1) the coronal structure of active stars. There are sufficient strong emission lines to define the emission measure curve with confidence. Four important conclusions important to the study of cool star coronas are found from analysis (Dupree *et al.* 1993) of the *Capella* spectrum:

1. A continuous distribution of plasma temperatures is present between 10^4 and $10^{7.2}$ K. Thus 1-temperature or 2-temperature models are incorrect for such systems.
2. The emission measure distribution (EMD) has a clear minimum near 10^6 K which differs from the solar example, and contradicts our understanding of the location of the maximum radiative losses of a collisionally dominated plasma in equilibrium.
3. A narrow enhancement in the EMD is present at $10^{6.8}$ K (the "bump"); this feature is relatively constant with phase (Dupree & Brickhouse 1995).
4. Electron densities are high ($10^{12} - 10^{13}$ cm^{-3}) at temperatures of 10^7 K as inferred from Fe XXI line ratios.

A major question is whether *Capella* is somehow unique, or whether such an emission measure distribution occurs in other binary systems.

4. Emission Measures for Other Binary Systems

A selection of binary systems composed of cool stars was incorporated into our Guest Observer program with EUVE, and additional spectra were obtained from the EUVE archive. The systems and their characteristics are given in Table 1 and the emission measure distributions are shown in Fig. 2. Similar enhanced features near $10^{6.8}$ K are found in the emission measure distribution of the rapidly rotating single giant stars 31 Com and AB Dor (Dupree *et al.* 1996).

Table 1. Parameters of Binary Systems

HD	Star	Sp. Type/Lum.	$P_{orbital}$ (*days*)	$P_{phtm.}$ (*days*)	Note
17433	VY Ari	K3–4V–IV	13.208	16.64	RS CVn star
21242	UX Ari	G5 V/K0 IV	6.44	P_{orb}	RS CVn star
22468	HR 1099	G5 IV/K1 IV	2.84	2.841	RS CVn star
34029	α Aur	G0 III/G8 III	104.0	8/80	RS CVn star
133640	44ι Boo	F9-G1 V	0.267	–	W UMa star
222107	λ And	G8IV-III	20.52	53.95	RS CVn star

Our studies show that the appearance of the *Capella*-like bump is most pronounced in the binary systems with short orbital periods or a short rotation period of one component ($\leq$ 13 days) or in individual stars with high rotational velocity (Hanson *et al.* 1995; Dupree *et al.* 1996). Although the orbital period of *Capella* is 104 days, the secondary star is rapidly rotating with a period of $\sim$8 days (Fekel *et al.* 1986) and the enhancement is pronounced.

5. Discussion: A New Coronal Structure

Rotation appears to be the significant physical parameter in producing an enhanced emission measure feature in cool star atmospheres. This feature is generally present in both rapidly rotating single stars and those systems with periods $\lesssim$ 13 days. However the temperature of the maximum and the width and strength of the enhancement differ from star to star. It is plausible to associate this feature with magnetic structures in a rapidly-rotating corona, in which case it could be dense and of small scale.

A measure of the electron density in the *Capella* system obtained from the Fe XXI lines indicates a high value, $\approx 10^{12}$ cm^{-3}. When the emission measure is evaluated with this high density, a small scale for the emission results – typically much less than a stellar radius. While there is some uncertainty because the contribution function for Fe XXI indicates the emission lines to be formed partly in the "bump" and partly at higher temperatures, either value of the emission measure yields a small scale for the emitting region.

This feature may be the coronal response in a rapidly rotating star to the high-latitude or polar spot frequently observed in the photosphere. For stars studied by Doppler-imaging techniques, spots are found at the poles [*cf.* HR 1099 (Vogt & Hatzes 1995; Donati *et al.* 1992); UX Ari (Vogt & Hatzes 1991)], *except* in the RS CVn system σ Gem (Hatzes 1993) which has an orbital period of 19.6 d. Figure 2 demonstrates that the longer period system, λ And, does not show such a well-defined coronal enhancement suggesting that the structure at coronal temperatures becomes less apparent in systems with orbital periods of $\sim$ 20 days. However, the spotted component of λ And has a photometric period of 54 days which exceeds the orbital period of 20.5 days. The disappearance of the "bump" in λ And may be controlled by the stellar rotation period much as its strength in the *Capella* system seems associated with the presence of a rapidly rotating secondary star. Under these conditions, the weakening of the coronal enhancement may occur over a wide range of periods.

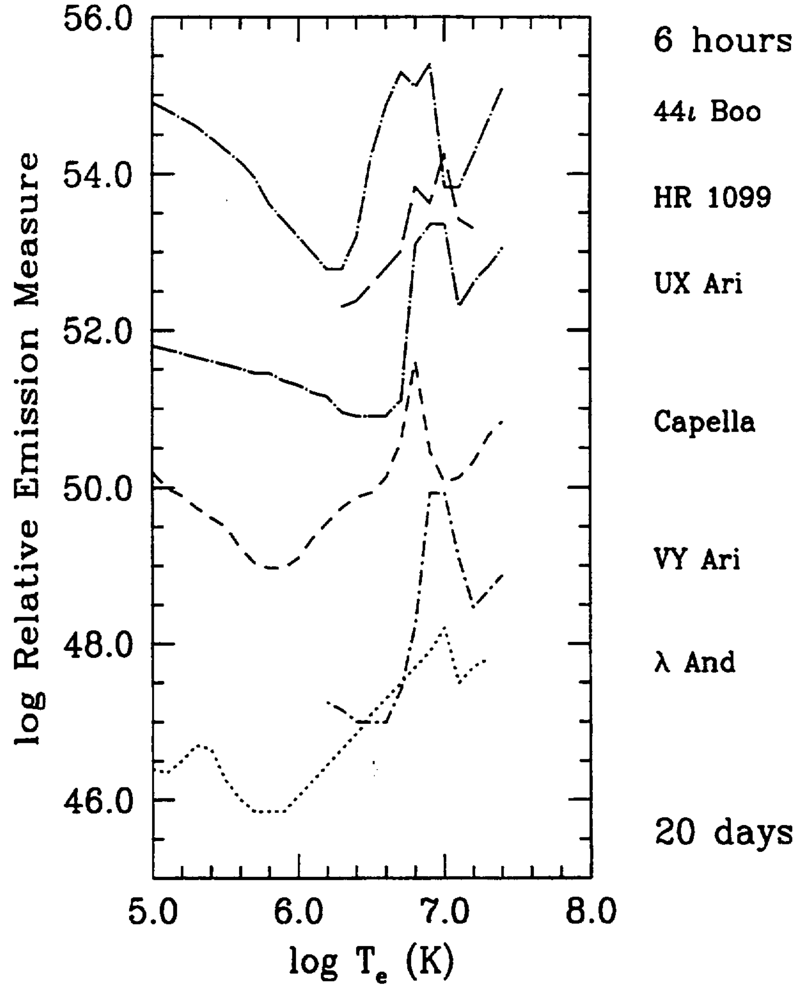

Fig. 2: The relative emission measure distribution for a variety of binary systems arranged in order of increasing orbital period. The curves have been shifted arbitrary amounts in the vertical direction. Here the "period" of the binary *Capella* is attributed to the rotational period of the rapidly rotating secondary of the system. Note that the system of longest period (λ And) does not show a well-defined "bump."

Our interpretation is strengthened by the observation of toroidal fields of $\approx$ 300 G in strength that circle the polar spot of HR1099 (Donati *et al.* 1992). Such a configuration on rapidly rotating stars would most likely result in a complex magnetic structure in the corona that could lead to excess heating. At coronal temperatures, with densities of 10^{12} cm^{-3}, fields of $\sim$ 150 G are needed for confinement. This value appears commensurate with observed photospheric fields. Additional *EUVE* spectra of systems with intermediate periods would be valuable for they could reveal the onset and development of these dense high temperature features.

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The EUV Transition Lines of Capella

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Abstract. Spectra of Capella (Alpha Aur; HD 34029) obtained with *EUVE* contain a number of lines formed at transition region temperatures, many of which are weaker than expected from UV line intensities. We construct a continuous emission measure distribution (EMD) using the UV lines, and compare the observed and predicted line intensities for the summed *EUVE* spectrum (280 ksec) of Capella.

1. Introduction

With the high S/N of the summed *EUVE* spectrum of Capella, we are able to measure weak lines of highly ionized Fe, and now have continuous coverage of Fe from Fe VIII—XXIV (Brickhouse 1995). Using Fe and the strong UV lines of Si, C, N, and O from *ORFEUS* (Hurwitz *et al.* 1995) and *HST* (Linsky *et al.* 1995), we construct a continuous EMD from $T_e \sim 10^5$—$10^{7.2}$ K. This model then allows us to predict other observable EUV lines.

2. Results

Table 1 lists the transition region EUV emission lines identified. Many lines are substantially suppressed in flux as compared with the fluxes predicted from the EMD such that: (1) the suppression increases with wavelength; (2) lower temperature lines show more weakening than higher temperature lines; and (3) lines formed above $\sim 10^{5.7}$ K show no weakening. We note some inconsistencies which are not currently understood, in particular the disagreement among the O VI lines. Weak lines in this spectral region from $T_e \sim 10^6$ K plasmas are not well known (Jordan 1995), and we are investigating possible blending contributions.

3. Discussion

Lyman continuum absorption is the simplest explanation for the suppressed EUV transition region lines. Interstellar absorption is ruled out by the high quality *HST* measurements of Linsky *et al.* (1993), as well as by the self-consistency of long wavelength, high temperature lines in the *EUVE* spectrum. Kanno & Suematsu (1982) have studied the wavelength-dependent weakening and center-to-limb variations of solar EUV lines. Their models require cool blobs with optical thicknesses of 3 to 4 overlaying the EUV emitting regions (but see Doschek & Feldman 1982; Judge *et al.* 1995). For Capella the supression is

Table 1. EUV Lines from the Transition Region ($< 10^6$ K)

Ion	λ (Å)	log T_{max} [a]	S/N [b]	Obs/Pred [c]
O III	507.4	5.0	4.7	0.02
O III	703.4	4.9	2.0	<0.53
O IV	238.6	5.2	3.2	0.07
O IV	554.4	5.2	6.7	0.04
O V	170.2	5.4	2.7	0.26
O V	172.2	5.4	2.8	0.29
O V	629.7	5.3	2.0	0.11
O VI	115.8	5.5	9.6	0.85
O VI	150.1	5.5	6.9	0.86
O VI	173.1	5.5	3.8	0.21
Si V	117.9	5.5	6.4	0.30
Si VII	275.4	5.8	3.3	1.07
Ne IV	541.1	5.2	1.8	0.04
Ne V	569.2	5.4	0.0	<0.02
Ne VI	122.5	5.6	9.8	1.08
Ne VI	401	5.6	7.5	0.30
Ne VII	465.2	5.7	4.0	0.76

[a] T_{max} is the temperature at which the line emissivity peaks. Note that for the steep emission measure distribution of the model, the lines are not necessarily formed predominantly at T_{max}.

[b] Signal/noise, with statistical uncertainties only. High order flux has been subtracted, and deblending has been taken into account. Some wavelengths given are for multiplets.

[c] Observed to predicted line fluxes (photon units), with abundances of Anders & Grevesse (1989).

much more dramatic than for the Sun. Lyman continuum absorption in the Capella atmosphere can also explain the weak of He II λ303.8 emission observed by Dupree *et al.* (1993). Microflare models of the Sun imply some Lyman continuum absorption from cooling gas above the surface (Raymond 1990).

To understand the transition regions in active binaries, particularly from $T_e = 10^4$ K to the emission measure minimum at $T_e \sim 10^6$ K, the role of downflows, fast winds, and nonequilibrium ionization needs to be addressed.

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